Improvement of High-Resolution Tropical Cyclone Structure and Intensity Forecasts using COAMPS-TC

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LONG-TERM GOALS

The long-term goal of this project is to develop a robust and hardened high-resolution air-ocean coupled tropical cyclone (TC) data assimilation and prediction system that is able to assimilate the wide variety of available *in-situ* and remotely-sensed observations in order to analyze and predict TC structure and intensity changes in an operational environment. TC intensity prediction by numerical models has shown little improvement over the past several decades and remains a formidable forecast problem. It is generally accepted now that while advancements in data assimilation and modeling have resulted in better analyses and predictions of steering flow, the processes that affect the structure and intensity of tropical cyclones are much more difficult for current numerical models to capture and reproduce. We also seek to improve prediction of TC intensity and structure change through an improved understanding and prediction of the TC outflow layer. The outflow layer is hypothesized to play a key role in tropical cyclone intensification and structural changes, and is investigated in a comprehensive manner using the innovative Global Hawk and satellite observations from the Hurricane and Severe Storms Sentinel (HS3) field program in the Atlantic during 2012-2014 and state-of-the-science tropical cyclone models.

OBJECTIVE

The objective is to develop, validate, and transition new methods to initialize a coupled tropical cyclone (TC) modeling system using advanced data assimilation and physical parameterization methods in order to achieve superior short and medium term forecasts of TC structure and intensity. Our approach is to leverage emerging data assimilation, modeling, and air-ocean coupling techniques, as well as observational results from the scientific community including the recent T-PARC/TCS08, ITOP, and HS3 field campaigns to build upon the existing modeling capabilities. We will develop multiple approaches to initialize the tropical cyclone including (from least to most sophisticated and challenging method): i) bogus initialization, ii) three-dimensional variational analysis (3D-Var) using synthetic observations, iii) dynamical initialization (TCDI), iv) an ensemble Kalman filter approach, and v) four-dimensional variational (4D-Var) analysis. The boundary layer and cloud microphysics parameterizations, which have a direct impact on the short-term forecasts as well as the analysis background fields, will be developed further and new methods will be tested.

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Several key scientific objectives are identified in relation to TC outflow dynamics, processes, and evolution: i) the coupling of the TC outflow with the inner-core convection and its relationship to intensity changes, ii) the evolution of TC outflow during trough interaction and its importance for accurate intensity prediction, and iii) the impact of observations (HS3 and satellite) in sensitive regions in the TC environment (including outflow regions away from the TC inner core) on predictions of TC intensity and structure.

APPROACH

Our approach is to integrate emerging data assimilation, modeling, and coupling techniques, as well as observational results from recent Office of Naval Research (ONR) and NASA field campaigns, into the existing framework in the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS[®1]) for applications to the analysis and prediction of TC position, structure, and intensity (referred to as COAMPS-TC). Our specific goal is to improve the COAMPS-TC analysis and prediction of intensity and structure. Specific technologies that will be developed, tested, and integrated into COAMPS for application to TC prediction in this project using COAMPS-TC are: (1) TC initialization and analysis techniques, (2) TC physical process parameterizations with particular emphasis on the microphysics, (3) air-ocean-wave coupling techniques, and (4) TC outflow science issues. The proposed project will also leverage other research that has taken place on COAMPS-TC including the recently completed COAMPS-TC RTP and the coupled modeling development through the Battlespace Environments Institute (BEI), which addressed the coupling of the COAMPS atmospheric model to the Navy Coastal Ocean Model (NCOM) and the SWAN and WWIII wave models using the Earth System Modeling Framework (ESMF). Also, the project will leverage scientific findings from the recent TCS08, ITOP, and the NASA/ONR HS3 program.

WORK COMPLETED

As a direct result of the research performed in this project, the skill of COAMPS-TC was considered superior to the existing Navy tropical cyclone prediction model, GFDN, and the COAMPS-TC code was transitioned to operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC). The COAMPS-TC became fully operational at FNMOC on 6 June 2013, which is a major milestone.

We are currently developing and evaluating several approaches to initialize the tropical cyclone vortex and environment including (from least to most sophisticated and challenging method): i) bogus initialization, ii) three-dimensional variational (3D-Var) analysis using synthetic observations, iii) dynamical initialization (TCDI), iv) an ensemble Kalman filter (EnKF) approach, and v) four-dimensional variational (4D-Var) analysis. Versions of several these methods, namely the 3D Var with synthetics and TCDI, have already been developed for COAMPS-TC and to varying degrees evaluated. Greater promise for more accurate initialization of the TC vortex exists for the more sophisticated EnKF and 4D-Var methods. The EnKF and 4D-Var methods will be advanced further as part of this project, and all of the methods will be statistically evaluated for a large set of TC cases using a variety of datasets include remote sensing. A two-stage dynamic initialization scheme for COAMPS-TC has been developed and continues to be evaluated. The scheme consists of a tropical cyclone dynamic initialization (TCDI) method in conjunction with a forward dynamic initialization

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(DI). This two stage dynamic initialization scheme improves both the vortex nonlinear balance and consistency in the transverse circulation, while reducing spurious gravity wave activity generated by interpolation and analysis errors in the 3D-Var scheme.

COAMPS-TC has been tested in both coupled and uncoupled modes over the past several tropical cyclone seasons in the Pacific and Atlantic basins. In these applications, the atmospheric portion of the COAMPS-TC system makes use of horizontally nested grids with grid spacing of 45, 15, and 5 km. The 15- and 5-km grid-spacing meshes track the TC center, which enables the TC convection to be more realistically represented on the finest mesh in an efficient manner. The forecasts are routinely disseminated in real time to NHC, JTWC, and HFIP researchers. The forecast graphics are available in real time at http://www.nrlmry.navy.mil/coamps-web/web/tc.

RESULTS

   a. COAMPS-TC Real-Time and Retrospective Model Forecasts

Real-time and retrospective COAMPS-TC forecasts have been conducted using U.S. Department of Defense High Performance Computing (HPC) platforms over the past several years. Verification results for the 2012 season in the Western Pacific basin are shown in Fig. 1, for a homogenous sample of real-time COAMPS-TC, GFDN, and HWRF forecasts. COAMPS-TC was overall the best-performing model in terms of intensity prediction in the 36-120 h range, an important period for forecasters and decision makers. This promising performance is a result of a large effort devoted to developing and improving COAMPS-TC over the past several years. While COAMPS-TC mean track errors were nearly as low as those of HWRF for lead times from 0-60 hours, the performance was not as good at later lead times. Track performance in the real-time 2012 forecasts motivated a renewed effort to improve COAMPS-TC track predictions for the 2013 season. A new methodology for generation of synthetic observations and improvements to the in-cloud vertical mixing and boundary layer parameterization led to improved track performance.

The new version of the model including the aforementioned improvements was tested over a large sample of retrospective Atlantic basin forecasts, for TCs in Aug-Oct of the years 2010, 2011, and 2012 (in conjunction with NOAA HFIP). Figure 2 shows a homogeneous comparison of retrospective COAMPS-TC forecasts and real-time HWRF, GFDL, and GFS forecasts. COAMPS-TC intensity results remain very encouraging. For track, COAMPS-TC is competitive with the other two regional dynamical models included in the comparison (HWRF and GFDL), while all the regional models remain behind the GFS. The new version of COAMPS-TC is now used for our experimental real-time predictions in 2013 and for the FNMOC operational predictions.

   b. COAMPS-TC Ensemble Forecasts Experiments

The COAMPS-TC ensemble system makes use of the community-based Data Assimilation Research Testbed (DART) capability developed at the National Center for Atmospheric Research, which includes various options for Ensemble Kalman Filter (EnKF) data assimilation. The COAMPS-TC DART system constitutes a next generation data assimilation system for tropical cyclones that uses flow-dependent statistics from the ensemble to assimilate observational information on the mesoscale.

The COAMPS-TC ensemble system was tested a for select group of storms in the W. Atlantic and W. Pacific regions. The system includes an 80-member COAMPS-TC cycling data assimilation ensemble on three nested grids with horizontal spacing of 45, 15, and 5 km. Lateral boundary conditions for the forecast ensemble were drawn from the GFS-EnKF ensemble forecast. Examples of probabilistic products for Hurricane Nadine are shown in Fig. 3, for track with and without dropsondes deployed by the HS3 Global Hawks, for forecasts from 0000 UTC 16 September 2012. These 120-h forecasts were performed using 20 members. Inclusion of HS3 dropsonde observations resulted in less track error and the dropsondes reduce the ensemble spread.

c. Coupled COAMPS-TC Forecast Experiments

The COAMPS-TC system was tested further in a fully coupled mode, interactive with NCOM, for the Office of Naval Research sponsored Interaction of Typhoon and Ocean Project (ITOP) during the summer and fall of 2010. The sea-surface temperature predicted by COAMPS-TC exhibited significant cooling during the passage of Typhoon Megi and Typhoon Fanapi due to enhanced mixing by the strong near-surface winds of the typhoon. The predicted cooling of the sea-surface temperatures of 2-4°C for both storms is in agreement with estimates from ITOP in-situ and remote sensing observations. The negative impact of the ocean cooling underneath the tropical cyclone can reduce the TC intensity and broaden the tropical cyclone wind field, which underscores the importance of properly representing these air-sea interaction processes.

d. Dynamic Initialization Development and Experiments

Further testing and evaluation of the track and intensity performance of the two-stage dynamic initialization scheme was conducted. Historical TCs were simulated using COAMPS-TC with the 3D-Var and synthetics initialization method (CNTL) and the two-stage dynamic initialization method (TCDI/DI). Improvements in both the initial vortex dynamic and thermodynamic balance and intensity and track errors were found by using TCDI/DI. In the TCDI/DI method, the TC initial balance is improved, and a much improved intensity forecast results in the first 6 hours. Both initializations were tested on multiple TCs in the western North Pacific and North Atlantic basins in 2010-2012. Statistics show that the TCDI/DI method reduced the average track errors slightly (~10-30 nm) and reduced the average intensity errors significantly (~25%). These results demonstrate that the TCDI/DI method can be used to improve TC intensity forecasts.

e. Analysis of Global Hawk Observations from the 2012 HS3 Field Campaign

One of our goals is to investigate the morphology of upper-tropospheric outflow jets, using the observations taken by the AV-6 Global Hawk in the 2012 HS3 field campaign. In particular, we were interested in analyzing the detailed vertical structure of outflow jets, as resolved by the AV-6 dropsondes. Here, we show results of our analysis pertaining to two AV-6 overflights of outflow jets, one from Hurricane Leslie and the second from Hurricane Nadine.

The overflight of Hurricane Leslie's outflow occurred during the ferry flight from Dryden to Wallops Island, on 6-7 September 2012. The flight made a loop around Leslie, dropping a series of sondes through an equatorward-directed outflow jet located between the center of the tropical cyclone and an upper-tropospheric trough. A height-latitude cross-section created based on the dropsonde data is

presented in Fig. 4. The highest wind speeds in the jet are located at 14 km, which is at the tropopause on the northern edge of the cross-section. This wind maximum at 14 km is coincident with the top of the cirrus cloud deck, as indicated in the CPL observations shown below the cross-section in Fig. 4. Above 14 km, at the top of the outflow jet, there is a very sharp shear zone in which the wind speed drops by approximately 20 m/s in 1 km of altitude. Figure 5 shows that this shear zone is associated with Richardson number values between 0.25 and 1 (blue shading), with embedded layers of Richardson number less than 0.25 (red shading).

During the 2012 field campaign, AV-6 made five lawnmower pattern flights around Hurricane Nadine. The first leg of the second Nadine flight (14-15 September 2012) was by far the best overflight of an outflow jet emanating from Nadine. This east-west oriented flight leg intersected the anticyclonically-curving outflow jet that emerged from the convectively-active northwest side of Nadine. A height-longitude cross-section created based on the dropsonde data from the aforementioned flight leg is shown in Fig. 6. As in the Leslie case described above, for Nadine the highest winds in the outflow jet are located just below the tropopause (where the isentropes begin bunching together just above 14 km). Above the wind maximum is a shear zone located in the lower stratosphere, for which the Richardson number is below 1 (see Fig. 7). Similar to the Leslie case, the Richardson number is driven to such low values by the strong shear.

f. Numerical Modeling: Impact of HS3 Observations on Tropical Cyclone Prediction

Here we apply the COAMPS-TC to better understand the impact of the HS3 dropsondes on predictions of tropical cyclone track and intensity. Two experiments were executed. The first experiment did not assimilate any of the HS3 dropsondes. The second experiment assimilated the HS3 dropsondes. In this second experiment, the density of the dropsondes was sufficient to initialize the tropical cyclone vortex, and thus synthetic observations were not used to initialize the storm, which is the typical method used for COAMPS-TC. Conventional satellite, surface, and radiosonde observations were assimilated in both experiments. The experiments were run over a 9 day period from 19-28 September, which featured 3 HS3 flights into Hurricane Nadine. The forecasts comprise approximately 30 verification samples of Hurricane Nadine. Figure 8 summarizes the results of the two experiments. The assimilation of the HS3 dropsondes improves the track prediction by over 50 nm at the 120 h lead time. The HS3 dropsondes have a larger positive impact on the maximum wind error and central pressure error, relative to the track error. For example, assimilation of the HS3 dropsondes reduces the maximum wind error from 15 knots to less than 10 knots at 48 h, with similar wind error reductions at later lead times. The central pressure error is reduced considerable from 16 hPa to 10 hPa at 48 h. We are currently analyzing these results further to better understand this strong positive impact that the HS3 dropsondes have on the forecast error.

TRANSITIONS

As a direct result of the research performed in this project, the skill of COAMPS-TC was considered superior to the existing Navy tropical cyclone prediction model, GFDN, and the COAMPS-TC code was transitioned to operations at Fleet Numerical Meteorology and Oceanography Center (FNMOC). The COAMPS-TC became fully operational at FNMOC on 6 June 2013. The tropical cyclone application of COAMPS transitioned to the 6.4 project within PE 0603207N (PMW-120), which has a focus on the transition COAMPS to FNMOC.

RELATED PROJECTS

COAMPS will be used in related 6.1 projects within PE 0601153N that include studies of tropical cyclone dynamics, air-ocean coupling, and boundary layer studies, and in related 6.2 projects within PE 0602435N that focus on the development of the atmospheric components (QC, analysis, initialization, and forecast model) of COAMPS. Also, this project is closely coordinated with a NASA supported project focused on the HS3 program.

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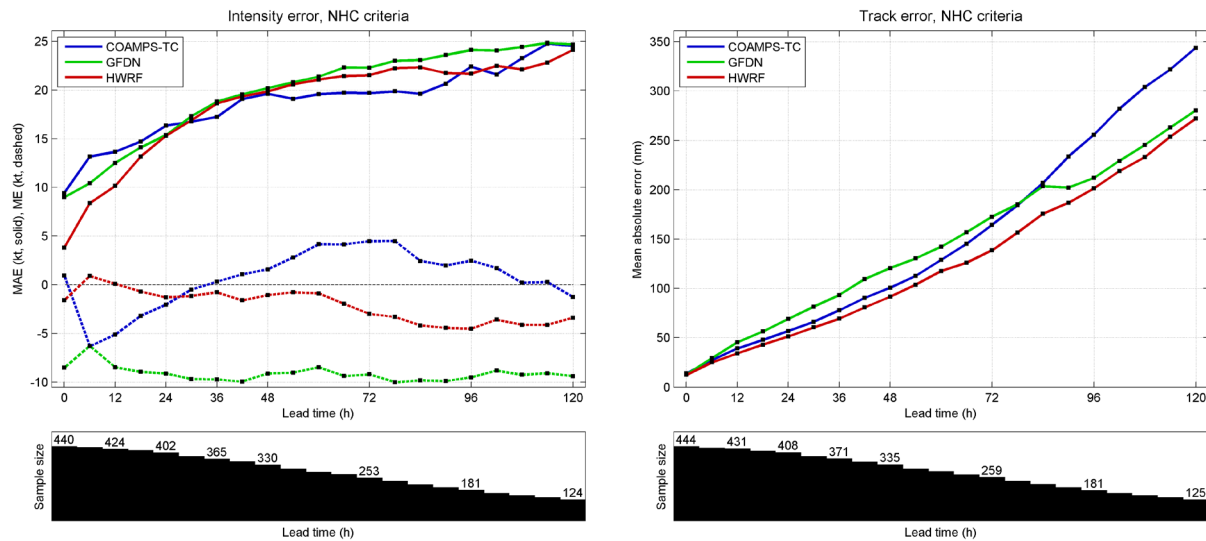
Figure 1: Track and intensity verification results for the 2012 Western Pacific basin season, for a homogeneous comparison of real-time COAMPS-TC, GFDN, and HWRF forecasts. The intensity results show mean absolute error (solid) and mean error (dashed), while the track results show mean absolute error.
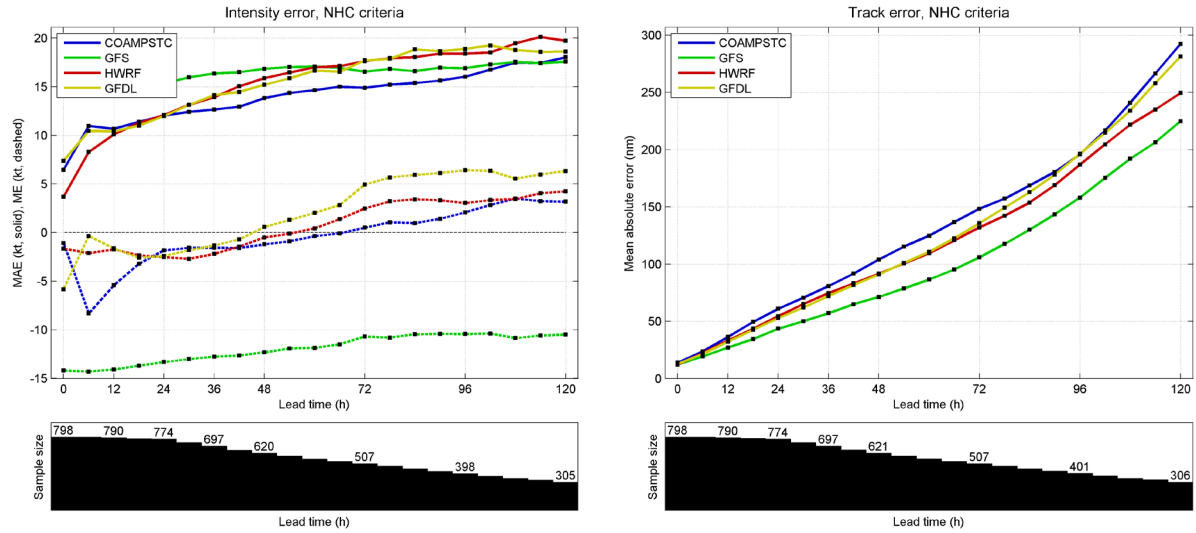
Figure 2: Track and intensity verification results for a large sample of Atlantic basin cases (2010-2012), for a homogeneous comparison of retrospective COAMPS-TC, and real-time GFDL, HWRF, and GFS forecasts. The intensity results show mean absolute error (solid) and mean error (dashed), while the track results show mean absolute error.
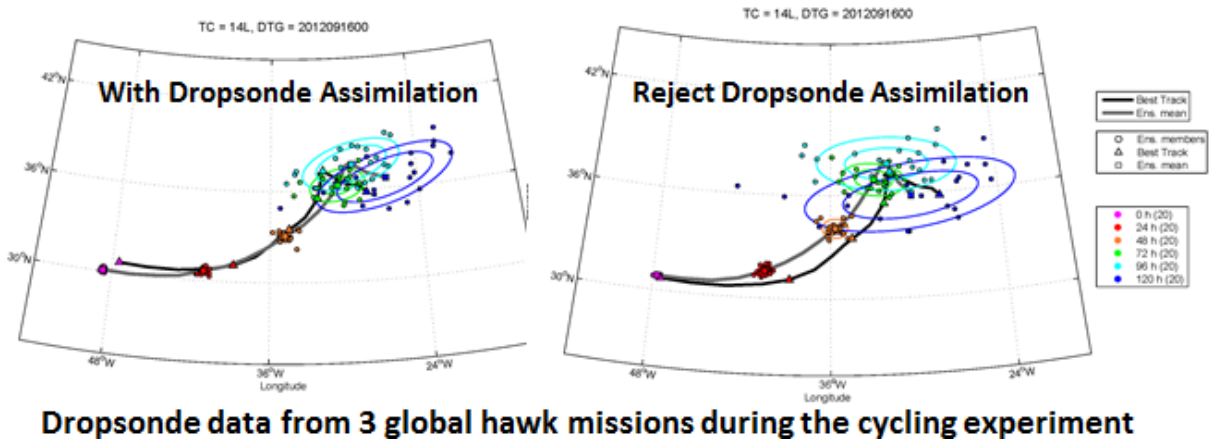

Figure 3. The impact of global hawk dropsonde assimilation on forecasts of Nadine using the 80 member EnKF COAMPS-TC forecasts. The left panel shows the track forecasts with the HS3 dropsondes and the right panel is without the dropsondes. The positions are shown by the color key to the right. The probabilistic track product shows the TC position from the individual ensemble members every 24 h and ellipses that encompass 1/3 and 2/3 of the ensemble member forecast positions.
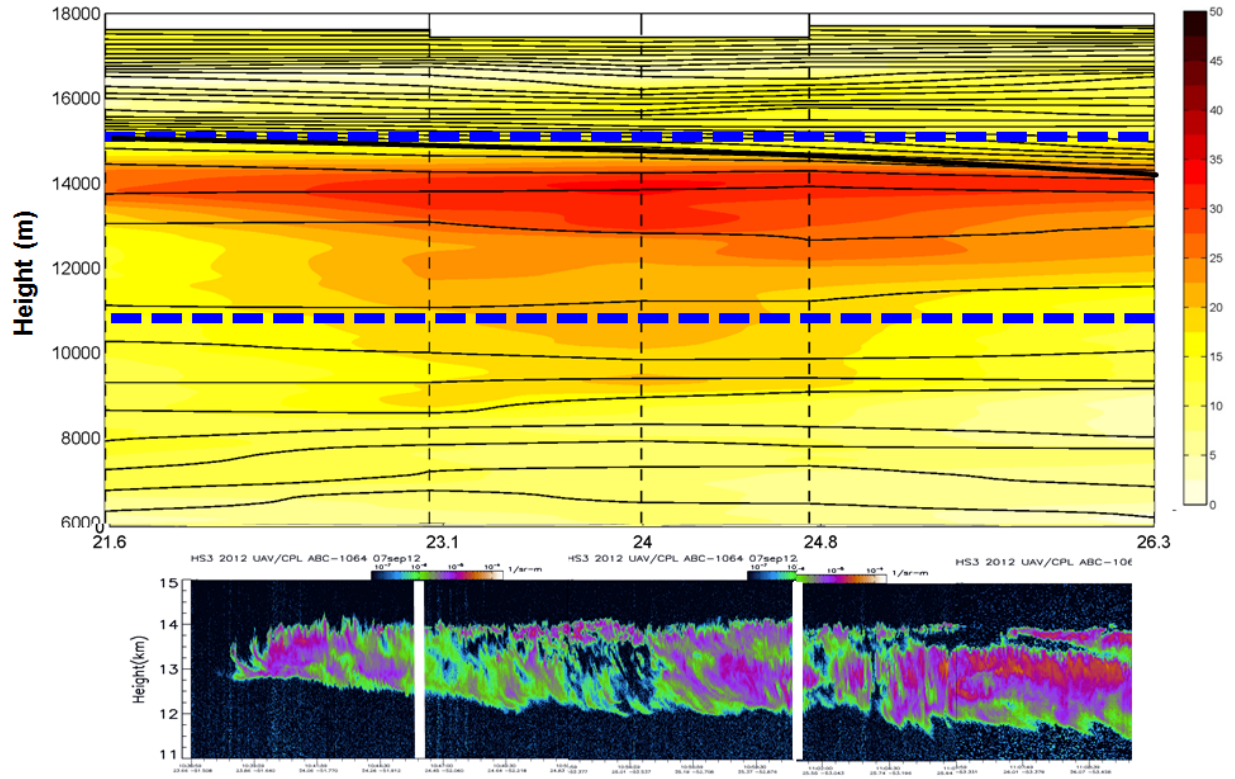
Figure 4. The upper plot shows a height-latitude cross-section created from five AV-6 dropsondes released during the ferry flight around Hurricane Leslie. The color shading indicates wind speed (contoured at 2.5 m/s intervals) and the black contours are isentropes (every 4 K). The thick black line indicates the approximate location of the tropopause. The dashed lines indicate the latitudes of the drops. The lower plot shows cloud observations from the CPL that correspond to the cross-section in the upper plot. The vertical extent of the lower plot (11-15 km) is demarcated by the dashed blue lines in the upper plot.
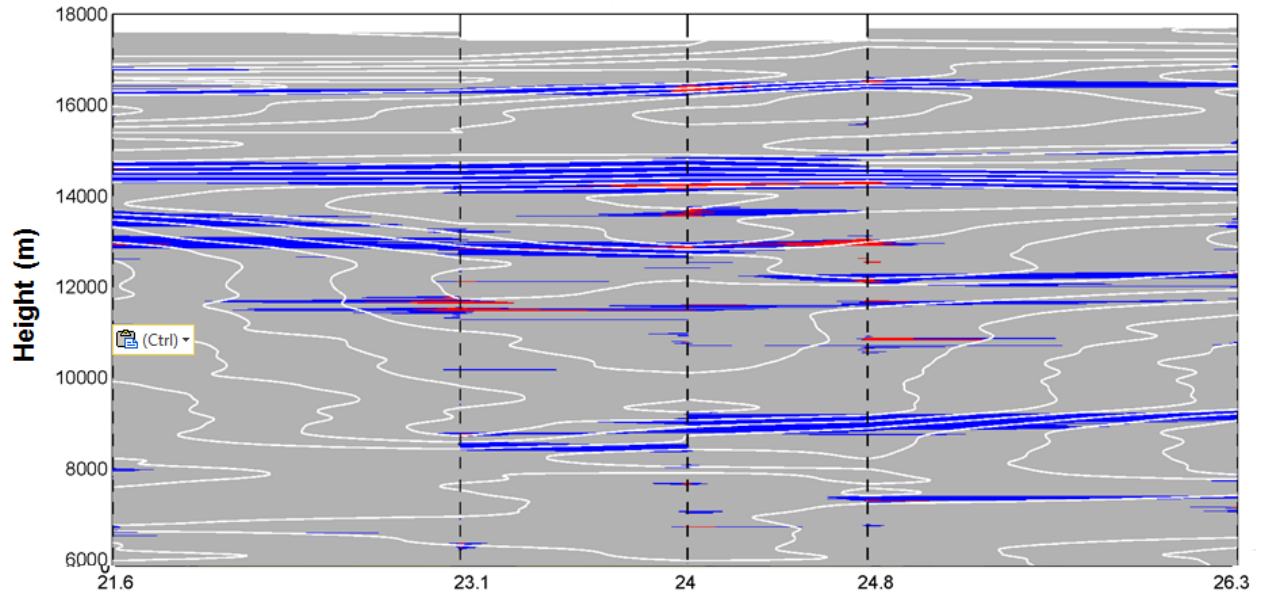
Figure 5: As in Fig. 4, a height-latitude cross-section created from five AV-6 dropsondes released during the ferry flight around Hurricane Leslie. The color shading indicates Richardson number (Ri): Gray for Ri > 1, blue for 0.25 ≤ Ri ≤ 1, and red for Ri < 0.25. The white contours are isotachs, drawn at 2.5 m/s intervals. The dashed lines indicate the latitudes of the drops.
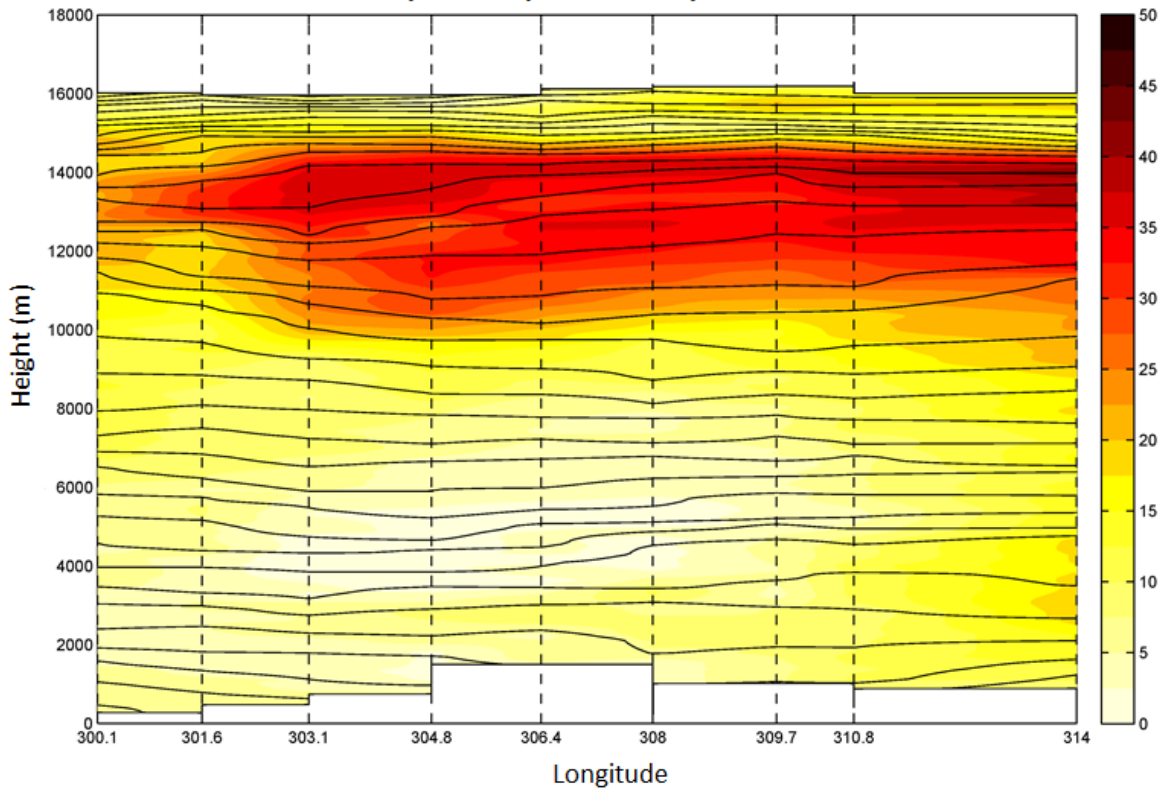

Figure 6: A height-longitude cross-section created from nine AV-6 dropsondes released during the first leg of the mission to Hurricane Nadine on 14-15 Sept. 2012. The color shading indicates wind speed (contoured at 2.5 m/s intervals) and the black contours are isentropes (every 4 K). The dashed lines indicate the longitudes of the drops.
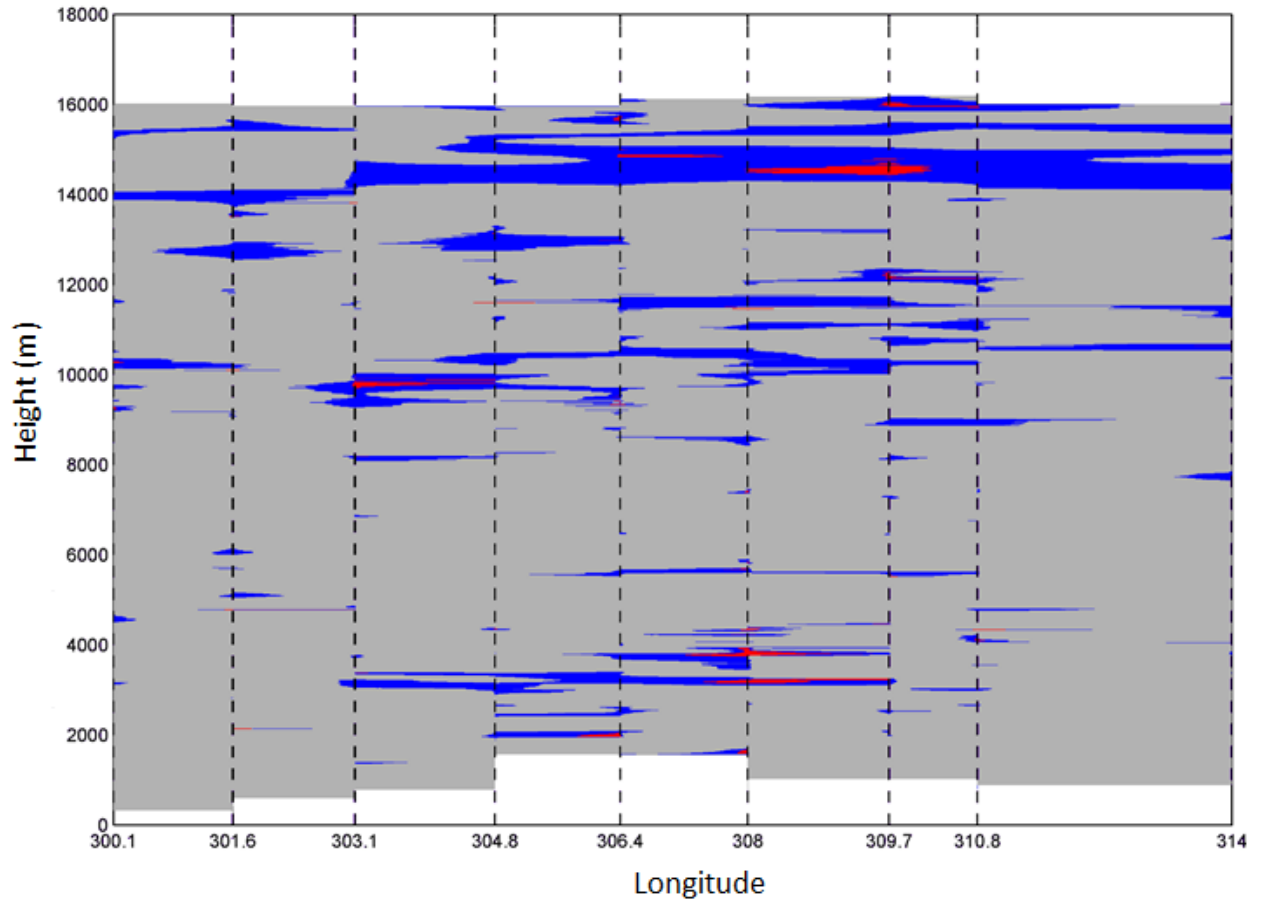
Figure 7: As in Fig. 6, a height-longitude cross-section created from nine AV-6 dropsondes released during the first leg of the mission to Hurricane Nadine on 14-15 Sept. 2012. The color shading indicates Richardson number (Ri): Gray for Ri > 1, blue for 0.25 ≤ Ri ≤ 1, and red for Ri < 0.25. The white contours are isotachs, drawn at 2.5 m/s intervals. The dashed lines indicate the latitudes of the drops.
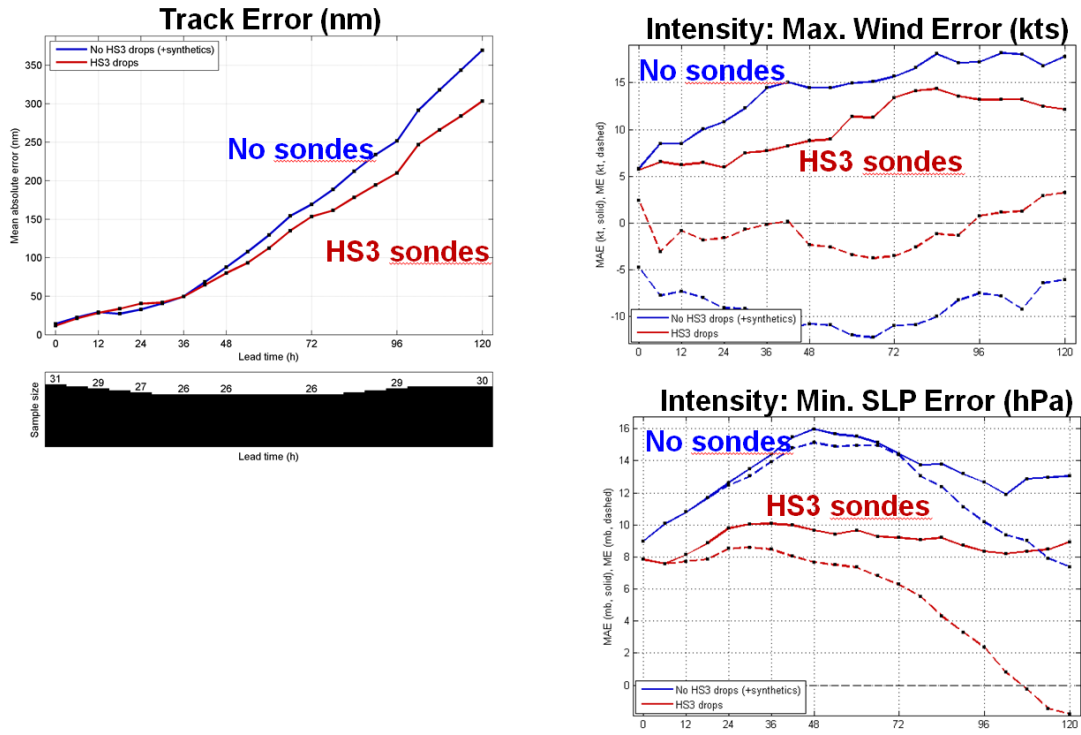
Figure 8: Track error (nm) (left panel) for Hurricane Nadine (Sep 19-28, 2012) as a function of forecast time for the experiment that used HS3 dropsondes in the assimilation system (red line) and the experiment that did not assimilate HS3 dropsondes (blue line). Wind speed mean absolute error (MAE, solid lines) (knots; 1 knot=0.514 m s^{-1}) (upper right) and minimum sea level pressure (lower right) as a function of forecast time for the two experiments. The number of cases is shown at the bottom.